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DESIGN OF LITESTEEL BEAM FLOOR JOISTS WITH WEB OPENINGS USING AN EQUIVALENT WEB THICKNESS METHOD

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Abstract: The LiteSteel Beam (LSB) is an innovative cold-formed steel hollow flange section. When used as floor joists, the LSB sections require holes in the web to provide access for various services. In this study a detailed investigation was undertaken into the elastic lateral distortional buckling behaviour of LSBs with circular web openings subjected to a uniform moment using finite element analysis. Validated ideal finite element models were used first to study the effect of web holes on their elastic lateral distortional buckling behaviour. An equivalent web thickness method was then proposed using four different equations for the elastic buckling analyses of LSBs with web holes. It was found that two of them could be successfully used with approximate numerical models based on solid web elements with an equivalent reduced thickness to predict the elastic lateral distortional buckling moments.

1. INTRODUCTION

OneSteel Australian Tube Mills (OATM) was the first to develop the hollow flange beams (HFBs) shown in Fig. 1(a). The efficiency of a HFB lies in the combination of its torsionally rigid closed hollow flanges and an economical manufacturing method based on simultaneous dual electric resistance welding and roll-forming process [1,2]. OATM recently introduced the mono-symmetric LiteSteel Beam (LSB) shown in Fig. 1(b) [3]. The new LSBs consist of two rectangular hollow flanges connected by a slender web. There are 13 LSB sections whose depth (d) varies from 125 mm to 300 mm while their hollow flange width (b_f) varies from 45 mm to 75 mm. The thickness of high strength steel (t) used in LSBs varies from 1.6 mm to 3.0 mm. The LSB section designation is based on $d \times b_f \times t$, eg, 300x60x2.0 LSB. Due to their light weight and cost-effectiveness, LSBs are increasingly used as floor joists in buildings.

Both HFB and LSB flexural members are subject to lateral distortional buckling effects in their intermediate span ranges as shown in Fig. 1 [1,2,4]. When employed as floor joists, LSB sections with higher depths and web openings are commonly used to provide access for inspection and various services. The moment capacities of floor joists made of slender LSB sections with larger spans depend on their elastic lateral distortional buckling moments. Several researchers have investigated and summarised the elastic lateral buckling behaviour of channel section beams [5-8] while Hancock et al. [9] and Bradford [10] have explored the effects of lateral distortional buckling on the strength behaviour of conventional I-sections.

Pi and Trahair [11] adopted energy methods to investigate the elastic lateral distortional buckling behaviour of simply supported HFBs subject to a uniform moment, and developed a simple closed-form elastic buckling solution for HFBs without web openings. They modified

the classical flexural torsional buckling formula by using the effective torsional rigidity. They then used a nonlinear inelastic method to study the lateral distortional buckling behaviour of HFBs, and developed member capacity equations for HFBs within AS 4100 guidelines [12].

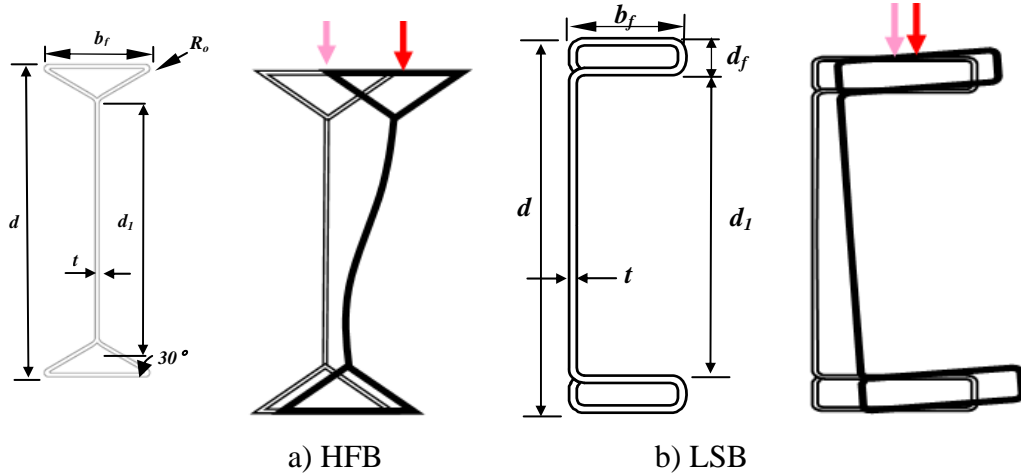


Fig. 1: Lateral Distortional Buckling Modes of HFB and LSB

At present, there is no accepted design method for LSB flexural members with web openings. Existing design methods such as AISI [13] deal only with channels with web holes and do not give the required elastic buckling moments and member moment capacities of LSBs. Seo and Mahendran [14] developed new design rules for the ultimate moment capacities of LSBs with web holes. These design rules were developed as a function of a non-dimensional member slenderness parameter (λ_d) defined as $\sqrt{M_y / M_{od}}$, where M_y is the first yield moment and M_{od} is the elastic lateral distortional buckling moment for a given LSB and web opening configuration. Hence there is a need to calculate M_{od} using simpler analyses.

In this study a detailed investigation was undertaken into the elastic lateral distortional buckling behaviour of LSBs with circular web openings subjected to a uniform moment using finite element and finite strip analyses. Validated ideal finite element models of LSBs with circular web holes were used first to study the effect of web holes on their elastic lateral distortional buckling behaviour. An equivalent web thickness method was then proposed for the elastic buckling analyses of LSBs with web holes. Four different equations were proposed to predict the equivalent web thickness, and their accuracy was investigated using finite element analyses. It was found that two of the proposed methods could be successfully used with approximate finite element and finite strip models based on solid web elements with an equivalent reduced thickness to predict the elastic lateral distortional buckling moments.

2. FINITE ELEMENT ANALYSES OF LSBS WITH WEB OPENINGS

Seo and Mahendran [14] used an ideal finite element model in a parametric study to generate member capacity curves suitable for the design of LSB flexural members with circular web holes. This model incorporated ideal support conditions, nominal imperfections and material properties and a uniform bending moment within the span. In this study this improved ideal model was used to study the LSB flexural members with circular web holes. Ideal finite element models of LSB flexural members without any web holes were also developed and used to study the moment capacity reduction due to the presence of web holes. The cross-section geometry of the ideal model was represented by the centreline dimensions based on the nominal external dimensions shown in Fig. 1 (b). The finite element modelling was con-

ducted using MSC/PATRAN to create the model and then submitted to ABAQUS [17] for the analysis.

2.1 Elements

Since the thin steel plate elements of LSB sections are subjected to local buckling while the LSB member is subjected to lateral distortional buckling effects, the chosen element must be capable of modelling these buckling phenomena and associated behaviour. The S4R5 three dimensional (3D) thin isoparametric quadrilateral shell element with four nodes and five degrees of freedom per node from ABAQUS was used to model the steel plate element as it is considered the most suitable for the finite element analysis. It is a small-strain thin shell element and can model large rotations accurately. This element can be more economical as it uses only five degrees of freedom (three displacement & two in-surface rotation components).

2.2 Discretization of the Finite Element Mesh

In finite element analyses, selection of mesh size and layout is critical. It is desirable to use as many elements as possible in the analysis. However, such an analysis will require excessive computer time and resources. In this analysis, adequate number of elements was chosen for both flanges and web based on detailed convergence studies in order to obtain sufficient accuracy of results without excessive use of computing time and resources.

By varying the element size, the adequacy of finite element mesh used in the model was studied. It was found that good simulation results were obtained by using the element size of approx. 5 mm×10 mm (width by length) for web and flange elements. Therefore an element size of approx. 5 mm×10 mm (width by length) was used in this study. The geometry and finite element mesh for a typical LSB model with web openings is shown in Fig. 2(a).

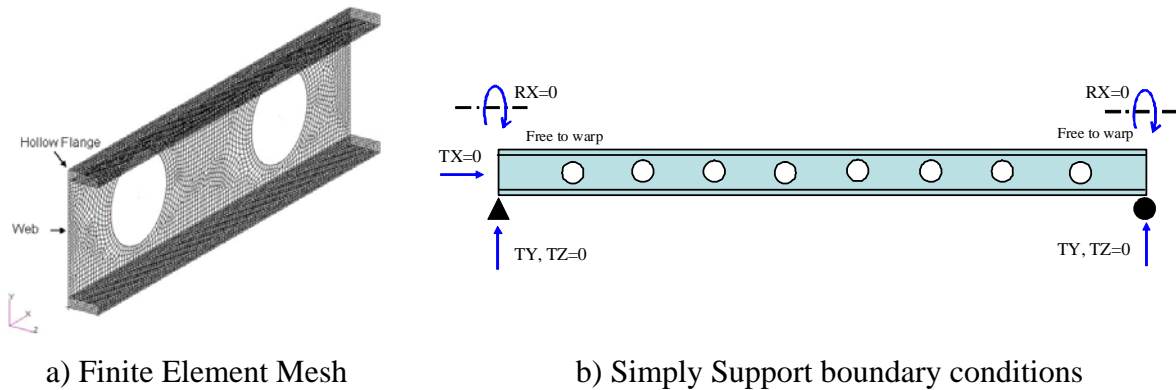


Fig. 2: Finite element mesh and boundary conditions of a typical LSB model

2.3 Load and Boundary Conditions

The objective of the finite element model was to provide “idealised” simply supported boundary conditions and a uniform applied bending moment, suitable for the development of design curves. Idealised support conditions for beams are required to satisfy the following requirements [15, 16]: a) Simply supported in-plane, ie., both ends fixed against in-plane vertical deflection, but unrestrained against in-plane rotation, and one end fixed against longitudinal horizontal displacement; b) Simply supported out-of-plane, ie. both ends fixed against out-of-plane horizontal deflection and twist rotation, but unrestrained against minor axis rotation and warping displacement. An illustration is provided in Fig. 2(b).

For the elastic buckling and nonlinear analyses the following boundary conditions were applied where $T[x, y, z]$ and $R[x, y, z]$ indicates translational and rotational constraints about x-, y-, and z-axis, respectively (“0” = constraint and “-” = no constraint). The pin support at the end was modelled by restraining appropriate nodal degrees of freedom $T[-, 0, 0]$ and $R[0, -, -]$. To simulate the symmetric conditions at mid-span, the following nodal degrees of freedom $T[0, -, -]$ and $R[-, 0, 0]$ were restrained. This combination simulates a simply supported condition with warping free and local flange twist restraint conditions as shown in Fig. 2(b).

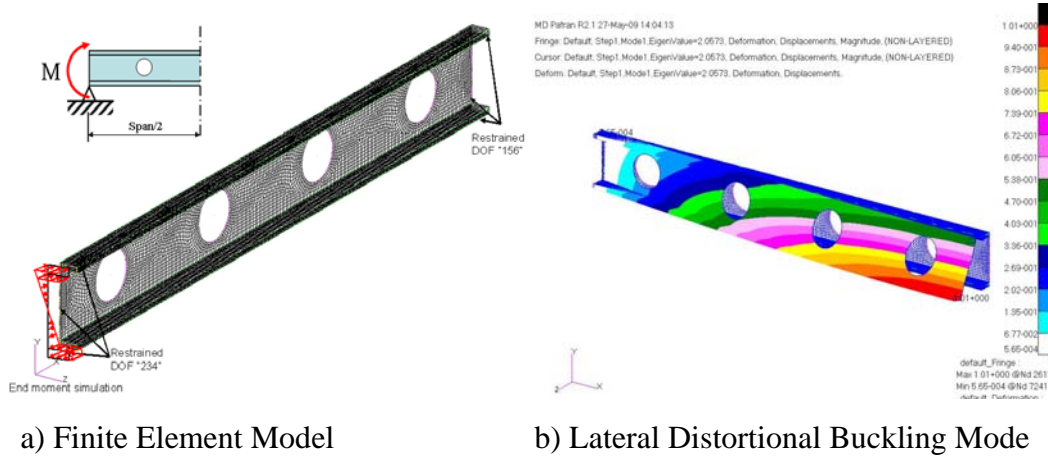


Fig. 3: Finite Element Modelling of 250x60x2.0LSB with Web Holes (Diameter = 150 mm, Spacing = 333 mm and Span = 1000 mm)

To simulate a uniform end moment across the section, linear forces were applied at every node of the beam end, where the upper part of the section was subject to compressive forces while the lower part was subject to tensile forces. The required uniform bending moment distribution within the span was achieved by applying equal end moments using linear forces at the end support. Fig. 3 (a) and (b) show the typical lateral distortional buckling modes obtained from the analyses of ideal finite element models with web openings.

Table 1: Elastic Lateral Distortional Buckling Moments of a typical LSB (250x75x3.0 LSB)

Span		2000 mm		4000 mm		6000mm		8000mm	
D	S	Number of Holes	M_{od} (kNm)	Number of Holes	M_{od} (kNm)	Number of Holes	M_{od} (kNm)	Number of Holes	M_{od} (kNm)
0	0	0	89.720	0	51.776	0	37.456	0	29.136
	100	20	86.845	40	50.146	60	36.322	80	28.271
	150	12	87.501	26	50.499	40	36.559	52	28.450
	200	10	87.934	20	50.750	30	36.733	40	28.581
	250	8	88.249	16	50.928	24	36.857	32	28.675
50	150	12	79.997	26	46.589	40	34.167	52	26.591
	200	10	81.397	20	47.338	30	34.588	40	27.043
	250	8	82.520	16	47.902	24	34.923	32	27.274
	333	6	83.920	12	48.627	18	35.374	24	27.596
	200	10	69.801	20	40.911	30	30.808	40	24.509
100	250	8	72.367	16	42.384	24	31.579	32	24.962
	333	6	75.172	12	43.917	18	32.429	24	25.503
	500	4	79.205	8	46.090	12	33.765	16	26.439

2.4 Elastic Buckling Analyses

Elastic buckling analyses were conducted to determine the critical elastic lateral distortional buckling moments for LSB flexural members with circular web holes and varying spans. Although there are 13 different LSB sections available, seven LSB sections that are most likely to be used in floor joist systems were selected in this study. They were non-compact sections (300x75x3.0 LSB), slender sections (300x60x2.0 LSB) and compact sections (250x75x3.0 LSB). Four different spans of 2000 mm, 4000 mm, 6000 mm and 8000 mm and four different sizes of circular web holes were considered. These web hole sizes included diameters of 50 mm, 100 mm, 150 mm and 200mm. Table 1 gives the elastic lateral distortional buckling moments (M_{od}) of one of the chosen LSB sections with various web hole configurations.

3. ELASTIC BUCKLING MOMENTS OF LSBS WITH WEB OPENINGS USING APPROXIMATE PREDICTION METHODS

3.1 Proposed Approximate Prediction Methods

The new design rules developed recently to determine the ultimate member moment capacities of LSBS with web openings [14] require the elastic lateral distortional buckling moments (M_{od}) for a given LSB and web hole configuration. As shown in Table 1, extensive data bases of M_{od} with web opening are required for design and research purposes. However, there is a need to develop a general prediction method for any given LSB section and web hole configurations. A possible prediction method is to replace the web plate of the cross-section with circular holes with a solid web plate having an equivalent reduced thickness. It is proposed that the effects of web hole configurations on the lateral distortional buckling of LSBS can be approximated by reducing the cross-section thickness in finite element analysis (ABAQUS, etc.) and finite strip analysis using the following four types of equations. It will then allow the numerical analyses to be undertaken with solid webs having an equivalent reduced thickness.

In the first method (M1) (Fig. 4(a)), an equivalent reduced thickness (t_{equ}) is determined for the full height solid web element along the full member length, based on the following.

$$t_{equ} = (A_{web} - A_{hole})t_{web} / A_{web} \quad (1)$$

In the second method (M2) (see Fig. 4(b)), an equivalent reduced thickness (t_{equ}) is determined for the web hole region only, based on the following equation.

$$t_{equ} = (1 - D/S)t_{web} \quad (2)$$

In the third method (M3) (see Fig. 4(c)), an equivalent reduced thickness (t_{equ}) is determined for both the web and flange elements based on the following equation.

$$t_{equ} = A_{flange}t_f + (A_{web} - A_{hole})t_{web} / (A_{web} + A_{flange}) \quad (3)$$

In the fourth method (M4) (see Fig. 4(d)), an equivalent reduced thickness (t_{equ}) is determined for the web hole region only, based on the following equation.

$$t_{equ} = (DL - A_{hole})t_{web} / DL \quad (4)$$

where, A_{web} = Area of web = $L \times d_1$, A_{flange} = Area of flange = $2(L \times b_f) + 2(L \times d_f)$, A_{hole} = Area of web holes = $\pi D^2 / 4 \times L / S$, d_1 = centreline dimension of web height, D and S = Web hole diameter and spacing, L = Member span

All four methods allow for the web hole size and spacing through a reduced thickness, and are based on the web hole area and spacing, and the selected areas of web and/or flange elements, except Method 2.

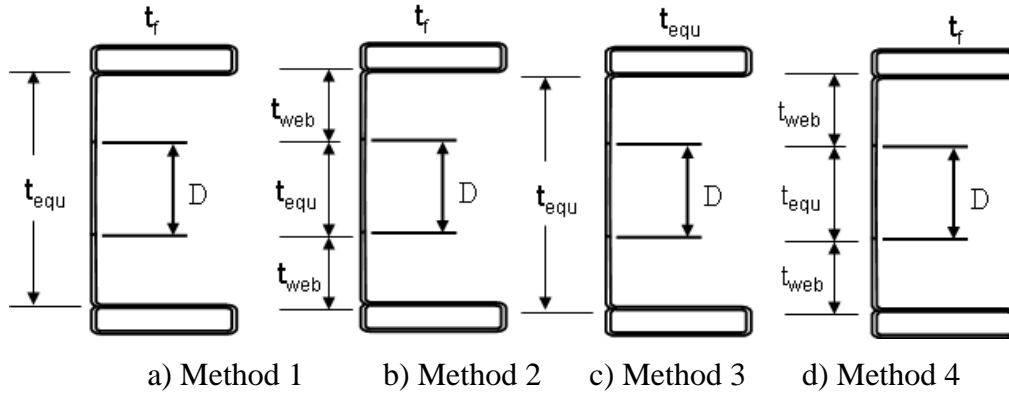


Fig. 4: Equivalent Thicknesses in Methods 1 to 4

3.2 Verification of the proposed methods

In order to determine the accuracy of the proposed equivalent thickness methods, the ideal finite element model of LSB described in Section 2 was used for three LSB sections (300x60x2.0LSB, 250x75x3.0LSB and 300x75x3.0LSB) with the equivalent plate thickness calculated from Methods 1 to 4 instead of modelling the web holes (approximate FEA model). Figs. 5 to 7 compare the elastic lateral distortional buckling moments obtained from these models with the accurate lateral distortional buckling moments obtained from similar ideal finite element models that included the actual web opening size and spacing. The horizontal axis is the ratio of web hole diameter to centreline dimension of web height (D/d_1).

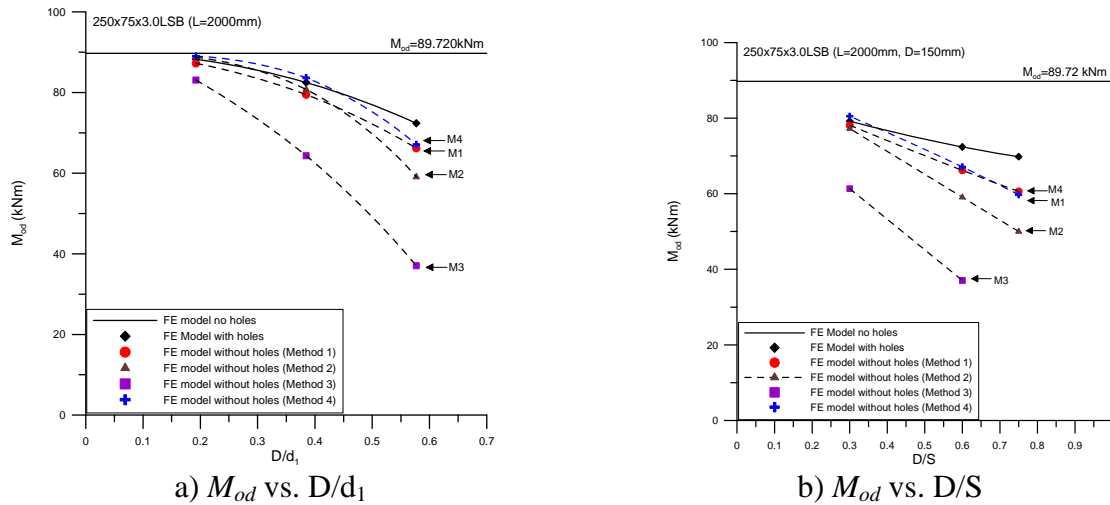


Fig. 5: Comparison of M_{od} from Approximate and Accurate Finite Element Models of 250x75x3.0 LSBs with Web Holes (Span = 2000 mm)

The ratio of M_{od} predicted by the accurate and approximate finite element models was calculated from the results. The mean and CoV of this ratio for Methods 1 to 4 are as follows: 0.9605 and 0.0375 (Method 1); 0.9265 and 0.1002 (Method 2); 0.6696 and 0.2911 (Method 3); 0.9831 and 0.0483 (Method 4). These results and Figs. 5 to 7 confirm that Methods 1 and 4 are accurate in predicting the elastic lateral distortional buckling moments of the selected slender and non-compact LSB sections with circular web openings using the approximate finite element models. As expected, Method 3 that includes both web and flanges is inaccurate. The implication of these results is that the equivalent reduced web thicknesses obtained based on Methods 1 and 4 can be used in the modelling of LSB flexural members with web holes when employing available FSA and FEA programs, thereby avoiding the complicated task of

explicitly modelling the web hole configuration. Method 4, which has a mean ratio of 0.9831, is considered to be the most accurate of the four methods, and hence LSBs with a reduced equivalent thickness in the web hole region alone (Fig.4) can be used in numerical modelling. In applications in which a single web element is to be used, Method 1 is recommended.

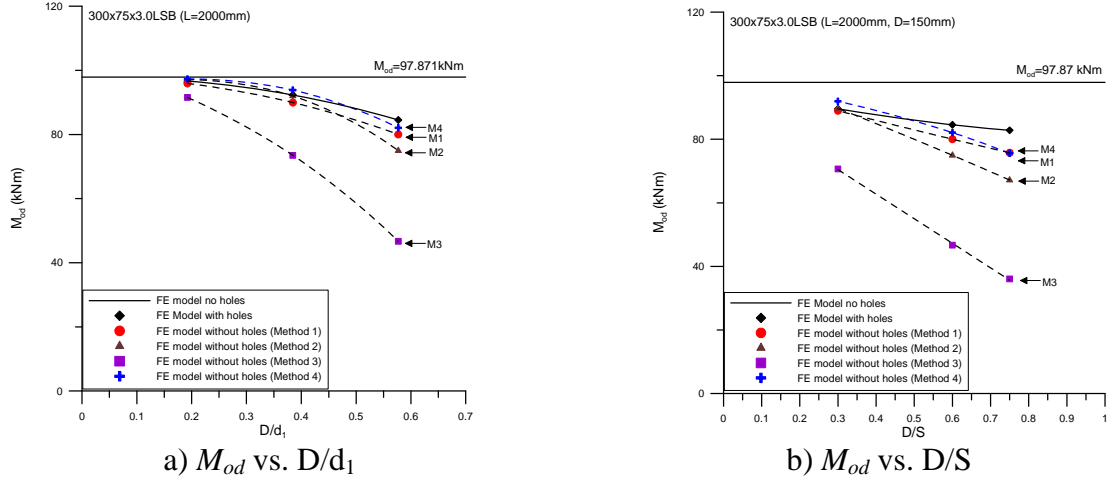


Fig. 6: Comparison of M_{od} from Approximate and Accurate Finite Element Models of 300x75x3.0 LSBs with Web Holes (Span = 2000 mm)

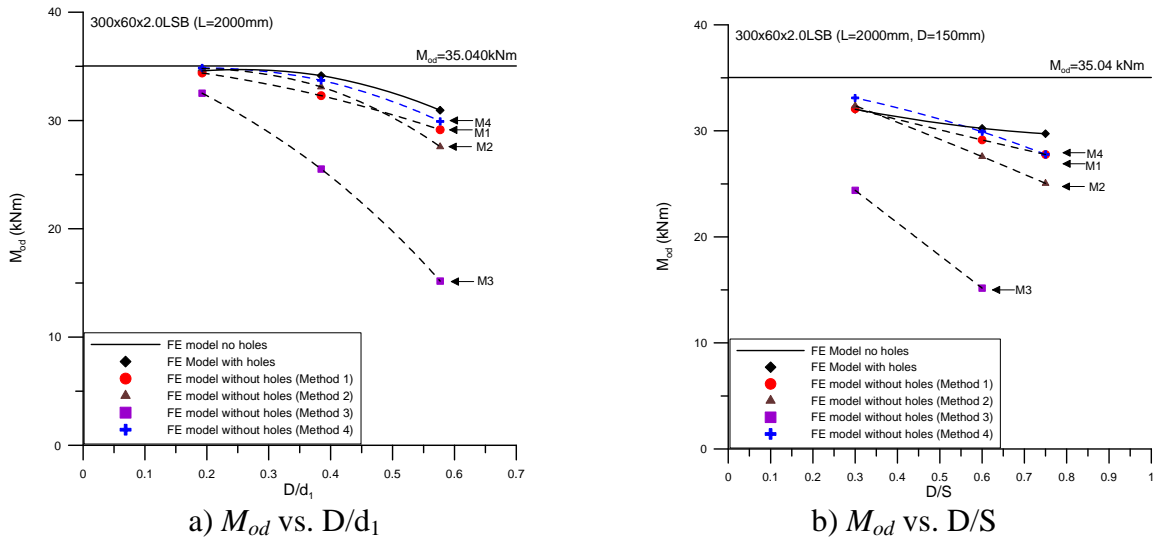


Fig. 7: Comparison of M_{od} from Approximate and Accurate Finite Element Models of 300x60x2.0 LSBs with Web Holes (Span = 2000 mm)

4. Conclusions

This study has presented the details of an investigation into the elastic lateral distortional buckling behaviour of LSBs with circular web openings subjected to a uniform moment using finite element analysis. Validated ideal finite element models of LSBs with circular web holes were used first to study the effect of web holes on the elastic lateral distortional buckling behaviour of seven LSB sections that are used commonly as floor joists and spans ranging from 1000 to 8000 mm. This paper presents the developed elastic buckling moment capacity data for these LSBs with different circular web hole and spacing arrangements. These results can be used in the design of LSB sections with varying web hole configurations.

An equivalent thickness method was then proposed for the elastic buckling analyses of LSBs with web holes. Four different equations were proposed to predict the equivalent plate thickness, and their accuracy was investigated using finite element analyses. Elastic lateral distortional buckling moments from approximate finite element analyses based on solid web elements with an equivalent reduced thickness were compared with those from accurate finite element analyses that included actual web hole and spacing configurations. It was found that two of the proposed methods could be successfully used with approximate finite element models to predict the elastic lateral distortional buckling moments of LSB floor joists with web openings.

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